

# Prospects of Direct Determination of $|V_{tq}|$ CKM Matrix Elements at the LHC

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## 1 Abstract

The prospects of measuring the CKM matrix elements  $|V_{tq}|$  with top quarks decays at the LHC are discussed here, with the top quarks produced in the processes  $pp \rightarrow t\bar{t}X$  and  $pp \rightarrow t/\bar{t}X$ , and the subsequent decays  $t \rightarrow Ws$  and/or  $\bar{t} \rightarrow W\bar{s}$ . As for the direct measurement of  $|V_{tb}|$ , there is also a lot of interest in the direct measurements of  $|V_{ts}|$  and  $|V_{td}|$ , as the absolute values of these CKM matrix elements can be modified by approximately a factor 2 from their SM values. Direct determination of these matrix elements will require a good tagging of the  $t \rightarrow s$  transition (for  $|V_{ts}|$ ) and  $t \rightarrow d$  transition (for  $|V_{td}|$ ) in the top quark decays, and a very large top quark statistics, which is available at the LHC. Lacking a good tagging for the  $t \rightarrow d$  transition, and also because of the small size of the CKM-matrix element,  $|V_{td}| = O(10^{-2})$ , direct measurements of  $|V_{ts}|$  at the LHC with main emphasis at the centre of mass energy  $\sqrt{s}$  of 14 TeV/ $c^2$  based on the PLB paper of Ali et al. [1] are shown. Alternative methods for direct  $|V_{tq}|$  determination at the LHC are also reported.

## 2 Introduction

Since the discovery of the top quark at Tevatron a lot of precise measurements have been undertaken at the two Fermilab experiments, CDF and D0 but also at the two LHC experiments ATLAS and CMS (see references in [1]). Among the highlights are the measurements of the top quark mass, currently having an accuracy of better than 1% [2], the  $t\bar{t}$  production cross section with about 5.5 % accuracy [3], and the observation of the electroweak single top production [4, 5].

The cross section  $\sigma(p\bar{p} \rightarrow t/\bar{t} + X)$  has provided the first direct measurement of the dominant CKM-matrix element  $|V_{tb}|$ . It is assumed that the CKM matrix elements  $|V_{td}|$  and  $|V_{ts}|$  are much smaller than  $|V_{tb}|$ , but no assumption is made about the unitarity of the  $3 \times 3$  CKM matrix. To obtain  $|V_{tb}|^2$ , the measured cross section is divided by the theoretical cross section for  $|V_{tb}| = 1$ . A direct combined CDF

and D0 measurement of  $|V_{tb}|$  using  $\sigma(p\bar{p} \rightarrow t\bar{t} + X) = 3.14(3.46)$  pb gave  $|V_{tb}| = 0.91(0.88) \pm 0.08(0.07)$  with  $|V_{tb}| > 0.79(0.77)$  at 95% C.L.

Direct determination of  $|V_{tb}|$  with the experiments at the LHC is expected to reach an accuracy of a few percent. The determination of  $|V_{tb}|$  with such an accuracy will be also very valuable to constrain beyond-the-SM physics models. In order to measure directly  $|V_{ts}|$  at the LHC, developing efficient discriminants to suppress the dominant decay  $t \rightarrow Wb$  is needed.

### 3 Results and Discussion

A necessary first step in the analysis is the tagging of the top events in which the  $W^\pm$  decay leptonically in order to reduce the jet activity in top quark decays. The emerging s-quark from the top quark decay  $t \rightarrow Ws$  and the collinear gluons, which are present in the fragmentation process, will form a hadron jet. Then tagging on the  $V^0$  ( $K^0$  and  $\Lambda$ ) in this jet, and measure their energy and transverse momentum distributions will give extra handles to suppress the dominant  $t \rightarrow Wb$  background.

Energetic  $V^0$ s are also present in the b-quark jets initiated by the decay  $t \rightarrow Wb$  and the subsequent weak decays  $b \rightarrow c \rightarrow s$ . However, in this case, the  $V^0$ s will be softer, they will have displaced vertexes (from the interaction point) and they will be often accompanied with energetic charged leptons due to the decays  $b \rightarrow \ell^\pm X$ . Absence of a secondary vertex and paucity of the energetic charged leptons in the jet provide a strong discrimination on the decays  $t \rightarrow Wb$  without essentially compromising the decays  $t \rightarrow Ws$ . Thus, the scaled energy and transverse momentum distributions of the  $K^0$ s,  $\Lambda$  and  $\ell^\pm$ , and the secondary decay vertex distributions ( $dN/dr$ ) are the quantities of principal interest.

The distance  $r$  traversed in the transverse plane (i.e. the plane perpendicular to the beam axis) by the b-quark before decaying, is smeared with a Gaussian resolution to take into account realistic experimental conditions. Two representative r.m.s. values have been assumed,  $\sigma$  (vertex) = 1 mm and 2 mm.

Detailed simulations are done using PYTHIA [8] to model the production processes, gluon radiation, fragmentation and decay chains, and the underlying events. A total of 1 million events were generated with PYTHIA 6.4 with  $|V_{ts}| = |V_{tb}| = 0.5$

Having generated these distributions, characterising the signal  $t \rightarrow Ws$  and the background  $t \rightarrow Wb$  events, a technique is used called the Boosted Decision Tree (BDT), a classification model used widely in data mining [6, 7] to develop an identifier optimised for the  $t \rightarrow Ws$  decays. Both BDT and a variant of it called BDTD (here D stands for de-correlated) are used, to discriminate the signal events from the large backgrounds. Briefly, the generated input is used for the purpose of training and testing the samples. The input is provided in terms of the variables discussed earlier for the signal ( $t \rightarrow Ws$ ) and the background ( $t \rightarrow Wb$ ). This information is used to

develop the splitting criteria to determine the best partitions of the data into signal and background to build up a decision tree (DT).

The signal ( $t \rightarrow Ws$ ) efficiencies are calculated for two cases called  $bb/bs$  and  $bs/ss$  for an assumed (Gaussian) vertex smearing with an r.m.s. value of 2 mm and 1 mm, respectively. Concentrating on the  $bb/bs$  case, when only one of the top (or antitop) quark decays via  $t \rightarrow W^+s$  these efficiencies lie typically between 5 % (for the 2 mm smearing) and 20 % (for the 1mm case) for a background ( $t \rightarrow Wb$ ) rejection of a factor  $10^3$ .

In Figure 1 (left frame), the BDTD response functions are shown, showing that a clear separation between the signal ( $t \rightarrow Ws$ ) and background ( $t \rightarrow Wb$ ) events has been achieved. The background rejection vs. signal efficiency for the  $pp \rightarrow t\bar{t}$  events is shown in the right frame of Figure 1 for both the BDT and BDTD classifiers, which give very similar results.

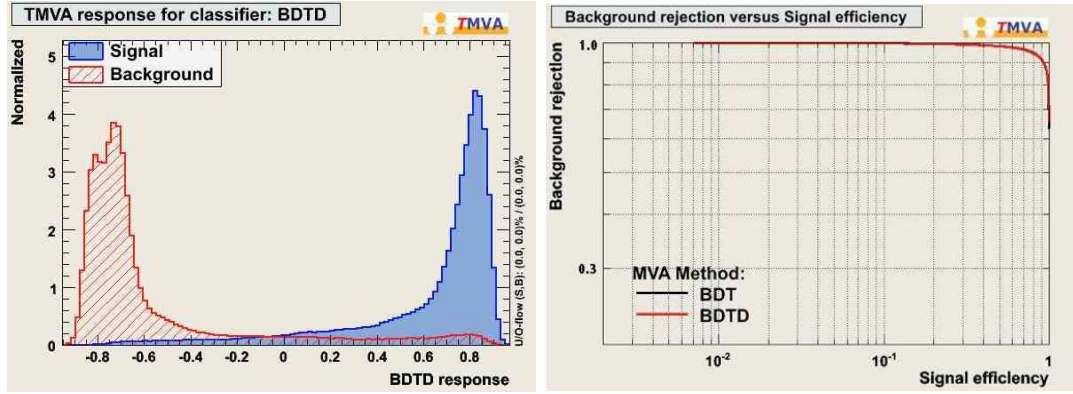


Figure 1:  $pp \rightarrow t\bar{t} + X$  at  $\sqrt{s} = 14 \text{ TeV}/c^2$ . Left frame: The normalised BDTD response. The signal (dark shaded) from the decay  $t \rightarrow Ws$  and the background (light shaded with dotted lines) from the decay  $t \rightarrow Wb$  are clearly separated. Right frame: Background rejection vs. signal efficiency calculated from the BDT(D) response.

This level of background rejection is necessary due to the anticipated value of the ratio  $|V_{ts}|^2/|V_{tb}|^2 \simeq 1.6 \times 10^{-3}$ . The required integrated LHC luminosity to determine  $|V_{ts}|$  directly is estimated to be  $10 \text{ fb}^{-1}$  at  $14 \text{ TeV}/c^2$ . Numerical analysis has been carried out for three representative LHC energies:  $7 \text{ TeV}/c^2$ ,  $10 \text{ TeV}/c^2$  and  $14 \text{ TeV}/c^2$ , here only the results for  $14 \text{ TeV}/c^2$  are mentioned, as the distributions for  $7 \text{ TeV}/c^2$  and  $10 \text{ TeV}/c^2$  are similar to the  $14 \text{ TeV}/c^2$  case.

## 4 Alternative methods for direct $|V_{tq}|$ measurements at the LHC

Alternative methods of determining the matrix elements  $|V_{td}|$ ,  $|V_{ts}|$  and  $|V_{tb}|$  at the LHC are based on the single top (or anti-top) production at the LHC. One attempts to determine these matrix elements from the cross section measurement by a simultaneous fit [9]. In the SM, one expects  $|V_{ts}|^2/|V_{tb}|^2 \sim 1.6 \times 10^{-3}$  and  $|V_{td}|^2/|V_{tb}|^2 \sim 6 \times 10^{-5}$ . In the example of realistic beyond-the-SM physics, these CKM matrix element ratios could be larger by a factor 4. Both in the SM, and in the four generation extension of it, the cross sections  $\sigma(pp \rightarrow tX)$  and  $\sigma(pp \rightarrow \bar{t}X)$  are completely dominated by the  $|V_{tb}|^2$  term. Hence, this proposal does not have the desired sensitivity to measure the matrix elements  $|V_{td}|$  and  $|V_{ts}|$  at the level of theoretical interest.

It has been recently suggested [10] that one may improve the sensitivity to  $|V_{td}|$ , using the top quark rapidity distributions, which are different for the valence d-quark initiated processes as opposed to the sea b-quark initiated processes. The described method based on the top quark decay characteristics to determine  $|V_{ts}|$  complements the existing proposal.

The ratio of the CKM matrix elements  $(|V_{td}|^2 + |V_{ts}|^2)/|V_{tb}|^2$ , that can be obtained by measuring the ratio  $R = B(t \rightarrow Wb)/B(t \rightarrow Wq)$ , where  $q = b, s, d$ , through the number of events with zero-, one-, and two b-tags in the process  $pp \rightarrow t/\bar{t}X$  [9] can be combined with the determination of the ratio  $|V_{ts}|^2/|V_{tb}|^2$  discussed before, to constrain (or measure) the quantity  $|V_{td}|^2/|V_{tb}|^2$ .

Finally, a model-independent extraction of  $|V_{tq}|$  matrix elements from top-quark measurements [11] is triggered by a recent D0 measurement of the ratio  $R = 0.90$ . It allows to extract the quark mixing matrix elements  $|V_{td}|$ ,  $|V_{ts}|$ , and  $|V_{tb}|$  from the measurement of  $R$  and from single-top event yields. This method provides information that can be directly used to put constraints on the four-family extended SM and other scenarios with new heavy quarks and to extract the top-quark width within these scenarios. It can be applied to single top-quark measurements at the LHC.

## 5 Summary and Conclusions

In this paper a case to measure the matrix element  $|V_{ts}|$  from the top quark decays is demonstrated. In order to reduce the jet activity in top quark decays, it was suggested to tag the  $W^\pm$  that decays leptonically,  $W \rightarrow \ell^\pm \nu_\ell$  ( $\ell = e, \mu, \tau$ ), and analyse the anticipated jet profiles in the signal process  $t \rightarrow Ws$  and the dominant background from the decay  $t \rightarrow Wb$ . A proposal to analyse the  $V^0$  ( $K^0$  and  $\Lambda$ ) distributions in the s- and b-quark jets concentrating on the energy and transverse momentum distributions of these particles was presented. The  $V^0$ s emanating from the  $t \rightarrow Wb$  branch have displaced decay vertexes from the interaction point due to the weak

decays  $b \rightarrow c \rightarrow s$  and the b-quark jets are rich in charged leptons. These distributions were used to train boosted decision trees, BDT(D). The BDT(D) response functions were obtained corresponding to the signal ( $t \rightarrow Ws$ ) and background ( $t \rightarrow Wb$ ). Detailed simulations undertaken with the Monte Carlo generator PYTHIA used to estimate the background rejection versus signal efficiency for three representative LHC energies  $\sqrt{s}=7, 10$ , and  $14 \text{ TeV}/c^2$ . A benchmark proved that with 10% accuracy for the signal ( $t \rightarrow Ws$ ) at a background ( $t \rightarrow Wb$ ) rejection by a factor  $10^3$  (required due to the anticipated value of the ratio  $|V_{ts}|^2/|V_{tb}|^2 \simeq 1.6 \times 10^{-3}$ ) can be achieved at the LHC  $\sqrt{s} = 14 \text{ TeV}/c^2$  with an integrated luminosity of  $10 \text{ fb}^{-1}$ .

In conclusion, a first study of its kind is presented here, showing that a direct measurement of  $|V_{ts}|$  in top quark decays is feasible at the LHC. BDT results in typically 10% efficiency for s-tagging with  $10^3$  b-jet rejection. An oversimplified exercise for an integrated luminosity of  $10 \text{ fb}^{-1}$  at  $\sqrt{s} = 14 \text{ TeV}/c^2$  taking  $\sigma(t\bar{t}) \sim 1 \text{ nb}$  gave an estimated expected significance of  $\sigma \sim 6$ . A similar exercise for single top decays gave expected significance  $\sigma \sim 3$ . Few alternative methods exist to measure directly  $|V_{tq}|$  matrix elements and are presented briefly in this paper. The  $|V_{ts}|$  method can complement these methods or directly be combined with them.

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